An ultra high resolution, electro-optical framing camera for reconnaissance and other applications using a 9216 by 9216 pixel, wafer scale, focal plane array

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ABSTRACT

A framing camera incorporating an ultra high resolution CCD detector array comprised of 9,216 x 9,216 pixels is discussed. The detector array measures 8 x 8 centimeters and has been scaled to be fabricated in one piece on a 5 inch diameter silicon wafer. Pixel size is 8.75 x 8.75 microns which gives 57 lp/mm resolution. The detector array features a two frame per second readout capability which allows collection of stereo imagery from very high V/H platforms. Image Motion Compensation is achieved by operating the frame readout clocks during the exposure interval in typical TDI fashion. The high geometric accuracy of pixel placement on the array yields a camera suitable for mapping, reconnaissance, space and astronomy applications. In this paper, measured detector array performance, detector array yield and overall camera performance are presented.

Keywords: Reconnaissance, Frame Camera, CCD, Electro Optical, Image Motion Compensation

1. INTRODUCTION

Airborne reconnaissance missions require sensors with both high resolution and large fields of view. This is driven by the requirement to image targets such as mobile missile launchers which require large fields of view to find, and when partially obscured in defilade require high resolution to identify. As reconnaissance cameras have begun to move away from film and toward the use of electro-optical detector arrays there has been a constant strain on the ability of detector manufacturers to build arrays of sufficient size and resolution to replace film. In spite of the difficulties, the desire to produce electronic imagery which is readily manipulated and may be data linked in real time to multiple users continues to urge us on.

Due to image smear and vibration effects in reconnaissance platforms, film cameras typically achieve about 50 lp/mm resolution on film in flight (although film itself can produce greater resolution.) Film reconnaissance cameras use film sizes of 2.25, 5 and even 9 inches wide with a useable width of 2, 4.5 and 8.5 inches. At 50 lp/mm a single frame of imagery from one of these cameras contains from 5,000 x 5,000 to as high as 21,000 x 21,000 "pixels" of information. The most typical cameras using 5 inch film (4.5 x 4.5 inch frames) produce the equivalent of 11,000 x 11,000 pixels. The 9,216 x 9,216 pixel detector array described here was designed as a "replacement" for the capability offered by 5 inch film in the reconnaissance camera. Further, the array with its high resolution and large field-of-view reduces the need to step and stare a camera to achieve extended coverage as would be required with a smaller array.

2. DISCUSSION

The Detector Array

The detector array has been designed to maximize the pixel count achievable on a 5 inch diameter silicon wafer while preserving high yield. The imager uses a special three layer polysilicon process and optimum 1.5 micron design rules to achieve optimum yield without stitching. The basic structure of the unit cell has been kept simple to assure yield and yet meet the performance requirements. The key performance requirements and actual results from measured detector arrays are shown in **Table 1**.

The detector array meets all of the requirements needed to yield a high resolution, high frame rate reconnaissance camera. Most notable are the excellent charge transfer efficiencies in both the vertical and horizontal shift registers which allow high speed readout of up to two frames per second (while retaining high resolution image quality) and the combination of low

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noise and high conversion efficiency of the output amplifiers. Low noise allows for a very large dynamic range in the imager (>4,000:1). The high conversion gain keeps small signals above the noise floor of the high speed digital electronics.

Parameter	Requirement	Measured
Pixel Count	9216 x 9216	Met
Architecture	Full Frame	Met
Pixel Size	8.75 x 8.75 micron	Met
Operating Mode	Framing W/IMC	Met
Frame Rate	> 1 Frame per Second	> 2 Frames per Second
Vertical CTE	> 0.999995	0.999999
Horizontal CTE	> 0.999995	0.999995
Dark Current	< 100 pA/cm^2	< 70 pA/cm^2
Pixel Readout Rate	> 25 MPS	> 40 MPS
Readout Noise @ 25 MHz	< 40 e- rms	< 25 e- rms
Conversion Gain	> 5 µV/e-	> 9 µ/Ve-
PRNU	< 5% Vsat	Met
DSNU	< 1 mV	Met
Quantum Efficiency	> 35% (0.55 to 0.8 nm)	Met
Net MTF @ Nyquist	50%	Met

Table 1. Key Performance Parameters Of the 9K Detector Array

Yield Results

The optimized array architecture produced excellent yield. To fabricate the arrays, a run of 22 wafers, with the potential to yield 22 devices, was processed. After using additional wafers for process stabilization, this run yielded 11 fully functional detector arrays. The five top arrays met the measured data and had dark current measured below 50 pA/cm^2. This success on the early run of arrays suggests high yield in production.

Array Packaging

Figure 1 is a full scale picture of the detector array installed in its demountable and alignable package. The array is precision mounted within the package to a flatness specification of +/- 0.5 mils. This allows operation with F#s < 2 while retaining acceptable focus over the entire array.

Potential Range of Frame to Frame Times

The range of frame to frame times over which the imager will be used is needed in order to access the potential impact of dark current charge accumulation during the interval. The frame to frame times for the detector array are determined by the Reconnaissance Aircraft's V/H, the lens focal length, the depression angle with respect to the horizon and the degree of overlap desired between frames. The equation governing frame to frame time is:

$$S = [Ht\ (feet) * Array\ Dimension\ along\ track\ (inches) * (1-OL)] / [V\ (ft/sec) * Sin\ (DA) * FL\ (inches)]$$

Where:

S = Seconds Between Frames
OL = Overlap Between Frames (0.12 or 0.56 are typical overlaps)
Ht = Height in Feet
V = Ground speed in feet per second
DA = Depression angle measured down from the horizon to the Near point of the image
FL = Focal Length of the Lens in inches

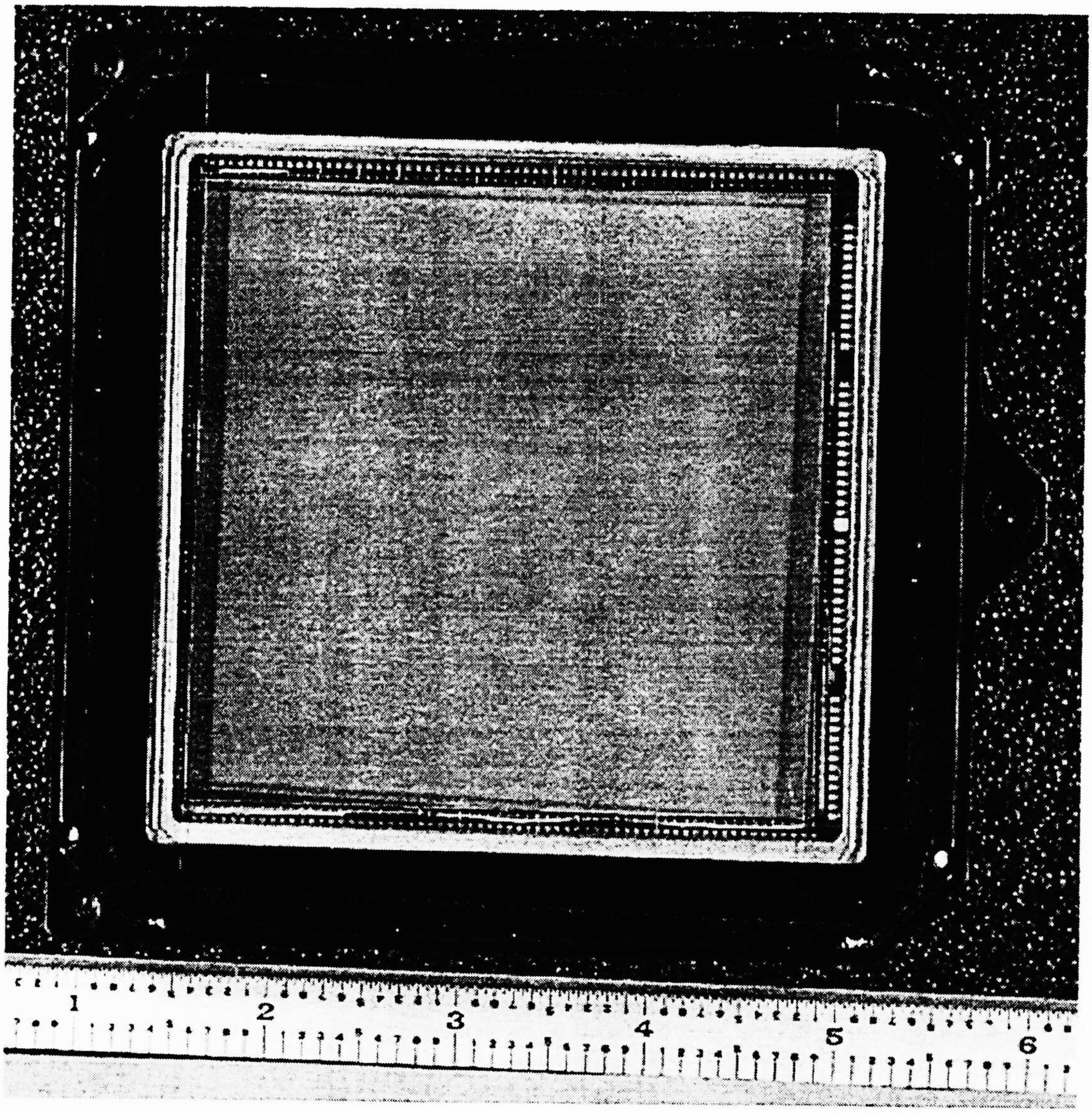


Figure 1. 9,216 x 9,216 Pixel Ultra High Resolution Detector Array in Cooled Package Shown Full Scale

A plot of this relationship for the Ultra High Resolution Framing Camera is shown in **Figure 2**. The camera is assumed to have a 6 inch focal length lens. The scale of the X-axis is given as the Velocity to Range ratio for the nearest point of the imaged frame. In this example, Frame to Frame times can vary from 0.5 seconds up to 6 seconds. The highest V/R supported by the camera with 6 inch lens is 0.93 which corresponds to a range of 1,000 feet at a speed of 600 KGAS. A six second dwell time occurs at a V/R of 0.077 which corresponds to a 6,000 foot range at 275 KGAS. Under these circumstances dark current in the detector could accumulate for up to 6 seconds between frames. The effect of this is reduced by cooling and/or by flushing the array of accumulated dark current charge generated during the dwell times between frames. Flushing is done if dwell times greater than 0.5 sec. are available. Over a total time of one second (0.5 second for readout plus 0.5 second for maximum unflushed pause time) the dark current accumulated in the Ultra High Resolution Imager at 25 C° is about 335 electrons per pixel. The number of accumulated dark current electrons are calculated from:

$$\text{Dark Electrons} = DC \times .0624 \times P^2 * S$$

Where:

DC = Dark Current in Pico Amps / cm^2 at the temperature of operation
0.0624 = Electrons per coulomb converted for units
P = Pixel Size in microns
S = Accumulation Time in Seconds

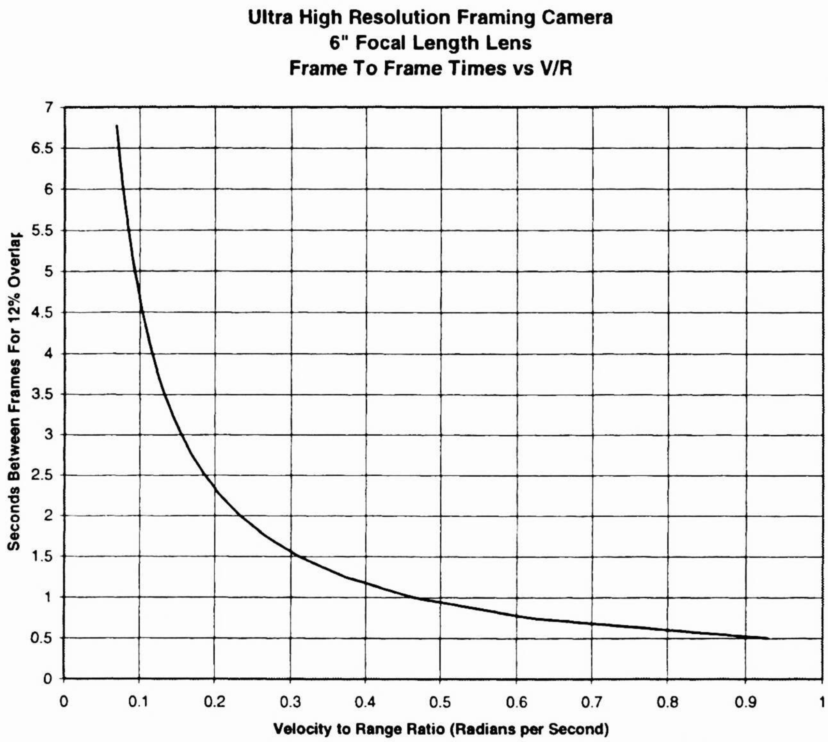
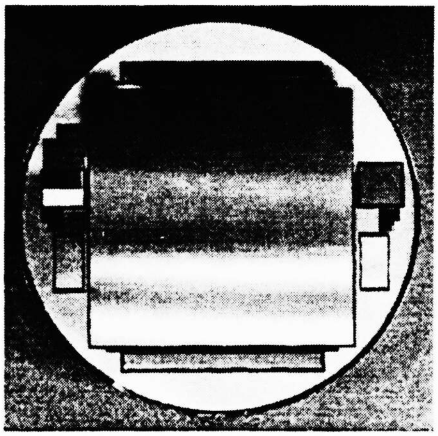


Figure 2. Ultra High Resolution Framing Camera, Seconds Between Frames vs. V/R

Detector Array Architecture

The 9K detector array is a single monolithic matrix of 9,216 x 9,216 pixels each with the same unit cell supporting a 3- phase CCD readout. The 3-phase structure is not preferential and can shift charge in either of two directions, toward the "top" of the Array or toward the "bottom". Horizontal output registers have been located at both the top and the bottom of the array to allow shift in either direction. **Figure 3** Illustrates the array architecture.



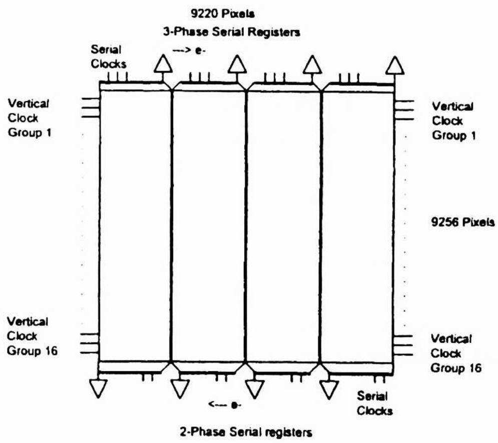


Figure 3. Ultra High Resolution Imager Showing Fit on 5 inch Wafer and Array Architecture

To minimize peak vertical array clock currents, the array is driven by 16 groups of 3-phase vertical clocks and each group is pinned out at both sides of the array. This substantially reduces the capacitance that each external clock driver is required to drive, and reduces the RC clock paths down to that represented by 1/2 of the array width. All sixteen of the vertical clock sets can be driven in parallel from the same set of digitally generated clocks. Alternatively, for higher speed readout, eight sets can be run in such a way as to transfer charge to the top half of the array while the other set of eight clocks are run in such a way as to shift the charge out of the bottom half of the array. When operating in this way, the frame readout rate of the array is doubled.

The horizontal registers at the top and bottom of the detector array are each divided into four parts. Each part thus serves to read out 2,304 pixels. Including the top and bottom, there are a total of eight outputs from the array. Each output can be clocked at up to 40 MHz. Presently the clocks are set at 25 MHz thus producing a data output rate from the array of 200 million pixels per second! For initial test flights the Ultra High Resolution Camera will be operated at a maximum readout rate of one frame per second using the horizontal output registers at one end of the array. The resulting 100 Mega pixel per second data stream is compressed to 2.33 bits per pixel which yields a data rate (including annotation overhead) of less than 240 Mbps that is compatible with current digital tape recorders.

Charge Transfer Efficiency

It is extremely important for the array to have high Charge Transfer Efficiency (CTE), particularly in the vertical direction. During vertical shift to the bottom of the array, image data must be moved through 9216 pixels to reach the horizontal output register. In the 3-phase structure of the vertical register, three shifts are required to move the charge one pixel. Transferring an image pixel from the top of the array to the bottom and into the horizontal register requires 9,216 x 3 or 27,648 shifts. Vertical charge transfer efficiency for the Ultra High Resolution Detector Array has been shown to be 99.9999%. Thus only 0.0001% of the image pixel's charge is left behind for each shift. Over 27,648 shifts the pixel from the top of the array will only leave behind 2.7% of it's charge. The horizontal register CTE is slightly less critical because data only moves through 1/4 the number of pixels to reach the output amplifier and two phase clocking is used. The measured horizontal CTE of 99.995% leaves behind 2.2% of the charge from the last pixel.

In both the vertical and horizontal registers the amount of charge left behind for the worst case pixel is extremely small. This is critical because the charge that is left behind reduces the signal in the pixel of interest and adds to the signal in the next trailing pixel. This will effectively reduce the contrast transfer function of the resultant output image. If for example, a high contrast pattern of alternating clear and opaque stripes, at the Nyquist spatial frequency, oriented parallel to the rows of the detector, were projected onto the array at 100% contrast, and phased so that the stripes were centered on the detector array pixels, the contrast transfer function (CTF) of the input pattern would be 100% as defined by the expression:

$$CTF = (Max - Min) / (Max + Min)$$

Where:

CTF = Contrast Transfer Function (Square Wave MTF)
Max = The signal level in the bar with Maximum brightness
Min = The signal level in the bar With Minimum brightness
Assumes Linear, Lossless Systems

The signal levels in a CCD detector array are typically expressed as numbers of electrons. In this case if Max started out as 1,000 electrons and Min as zero the CTF equals 100%. After shifting through the array the last pixel pair will have 973 electrons in the Max pixel and 27 electrons in the Min pixel. The resultant CTF is 94.5% for a loss in CTF of 5.5%. This is relatively insignificant and the Ultra High Resolution Imager shows excellent CTF from top to bottom. To illustrate the importance of good CTE, **Figure 4** shows CTF at Nyquist for the last pixel pair as a function of CTE.

It is clear that an extremely good charge transfer efficiency is needed to preserve resolution in a large scale imager. Small fractions of charge left behind can accumulate into a large CTF loss at the Nyquist Frequency after 27,000 shifts. The architecture of the Ultra High Resolution Imager unit cell assures this.

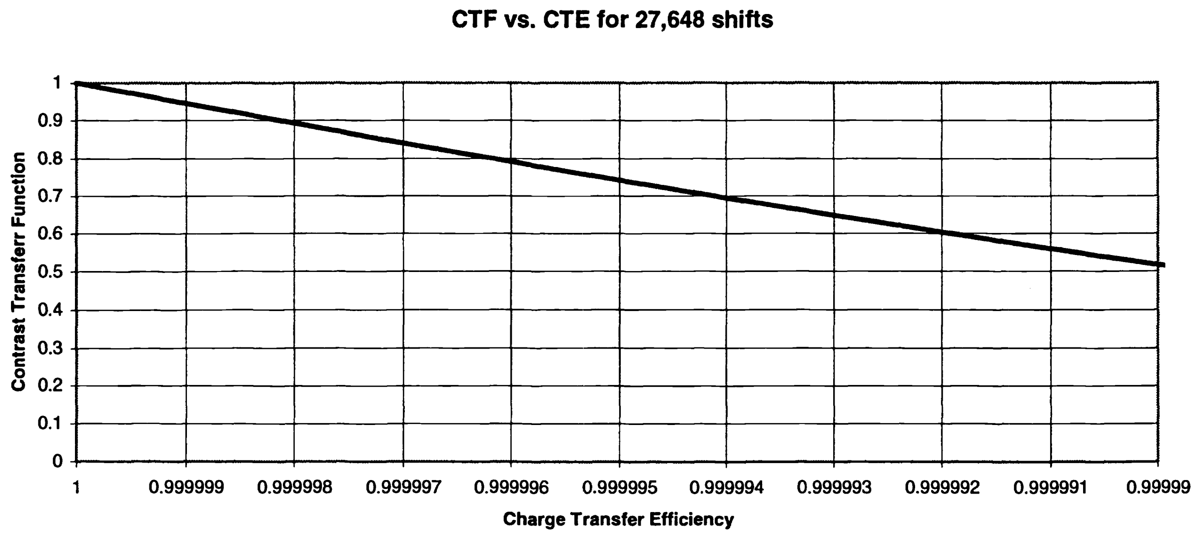


Figure 4. A Charge Transfer Efficiency of 99.9999% preserves good Vertical CTF in the Ultra High Resolution Imager

Total performance of any electro-optical system is typically determined by cascading the Modulation Transfer Functions (MTFs) from all uncorrelated, linear sources. MTF is sine wave response whereas CTF is square wave response. Since it is usually easier to produce bar targets that are square waves, response measured using square wave targets is mathematically converted to sine wave response. For a CCD at Nyquist, multiplying the CTF by $\pi/4$ is a sufficiently accurate conversion. Applying this conversion to the CTF at the midpoint of the detector array (half the shifts), the average loss in MTF in the vertical direction is 2%.

Seamless Imagery

Reconnaissance imagery requires a high level of confidence that complete scene coverage is achieved without artifacts. This is met by the wafer scale Ultra High Resolution detector with no seams or discontinuities between the sections of the imagery that are read by each of the horizontal registers. The CCD layout within the body of the detector array makes no distinction between any of the 9,216 columns of pixels. During readout, every pixel is picked up by one or another of the horizontal output registers.

Optical Crosstalk

The overall MTF Specification for the imager is >50% for all sources. Contributors to MTF reduction in the detector array include the effects of sampling, CTE and Optical Crosstalk. Sampling MTF at the Nyquist frequency is 0.64 and the effects of CTE produce an average MTF of 0.98. This leaves a budget of 0.8 for Optical Crosstalk. Optical Crosstalk occurs when incident photons penetrate deeply into the CCD array before generating a corresponding photoelectron. Photoelectrons which are generated deep within the array must drift up to the potential wells on the surface and may not be collected within the pixel area where the photon struck. Thus, the incoming signal is partially spread to adjacent pixels. Within silicon, longer wavelengths, such as those from 0.7 to 0.9 microns, penetrate more deeply creating more crosstalk. Unfortunately these are also the wavelengths where the detector array continues to have high quantum efficiency and hence we do not wish to filter them. Thinning and backside illuminating the array is one method of dealing with this problem but excessively risky in all but the most demanding applications.

However, the Ultra High Resolution Array architecture is a careful balance of well depth, oxide thickness and the use of Non MPP operation which yields the best balance of charge handling capacity, transfer speed and minimized crosstalk. The array meets the overall specification of 50% MTF when illuminated with white light bar patterns at a color temperature of 5500 K°. This color temperature produces energy in the spectrum which closely matches that of sunlight. **Figure 5** Illustrates the energy distribution of 5000 K° light and the normalized response of silicon showing the mismatch in peaks.

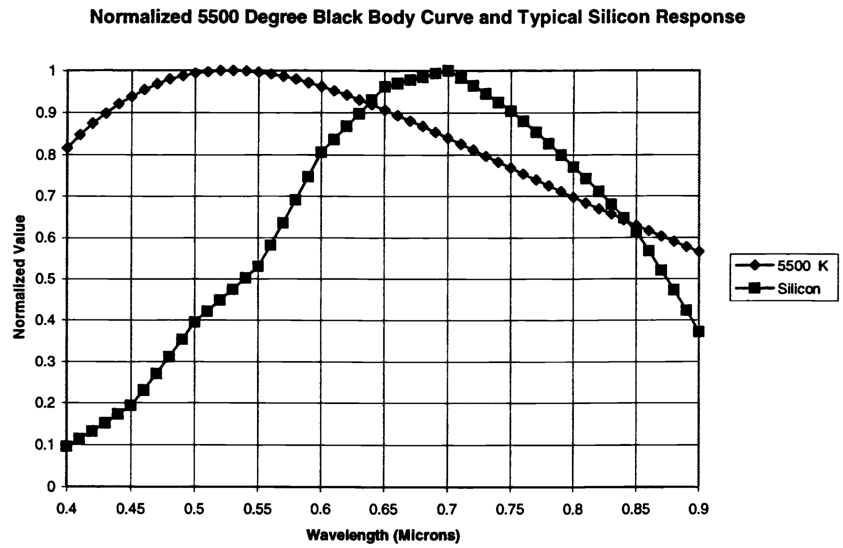


Figure 5. Relative Comparison Between the Response of Silicon and The Typical Illumination From Sunlight

Camera Block Diagram

A block diagram of the initial test camera and the associated airborne electronics units is shown in **Figure 6**. Separate electronics units include the Camera Body Unit (CBU), Imaging Electronics Unit (IEU), the Processing Electronics unit (PEU), the Tape Recorder Electronics Unit (REU), the Tape Transport Unit (TTU) and optional use of the AN/ASQ-197 interface with cockpit control panel or a Laptop control unit.

The CBU contains interchangeable camera lens units and an improved high performance shutter.

The IEU attaches to the CBU. The IEU contains the detector array and all required drive electronics for the array. Four to eight channels of high bit rate, 12 bit per pixel, digital data are output from the unit. The IEU measures 10.32" long by 13.12" wide by 2.62" high.

The PEU performs all control functions, array signature correction, data compression and recorder interface. Control functions include exposure time calculation, frame rate and Image Motion Compensation clock rates. The PEU measures 8.38" long by 15" wide by 9.19" high. Array signature correction performed in the PEU reduces signature "noise" in the output video which is usually difficult for data compressors to handle. Elimination of this noise in the camera electronics allows for more compression with less error.

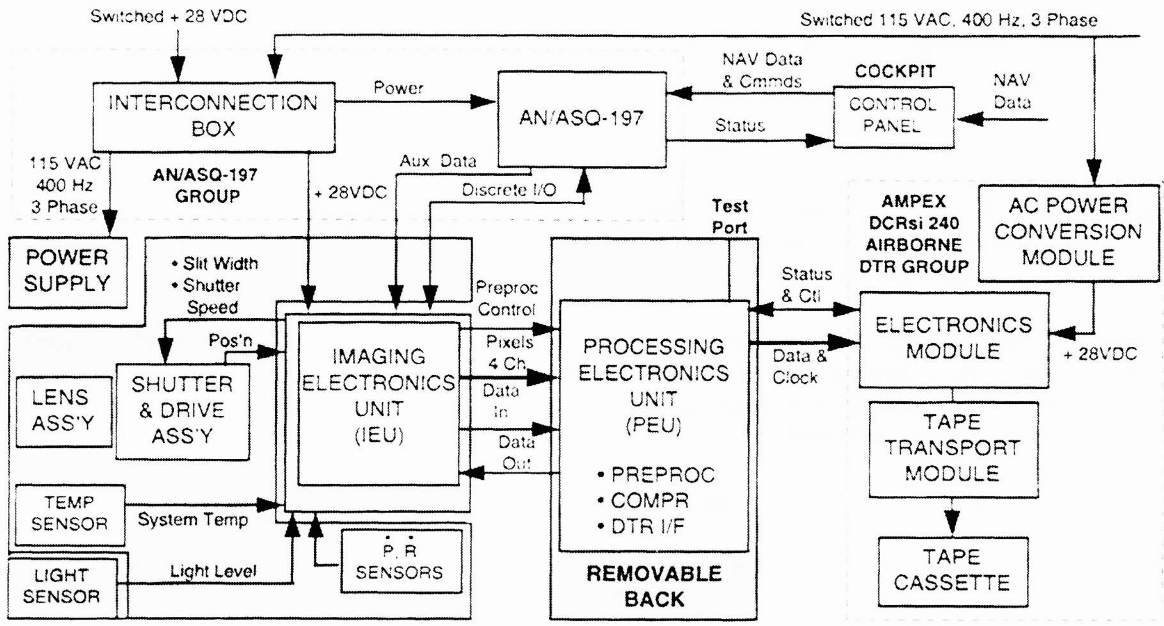


Figure 6. Ultra High Resolution Framing Camera Airborne System Block Diagram

Hardware

The fully integrated test camera including the associated processing electronics unit and digital data recorder is shown in **Figure 7**.

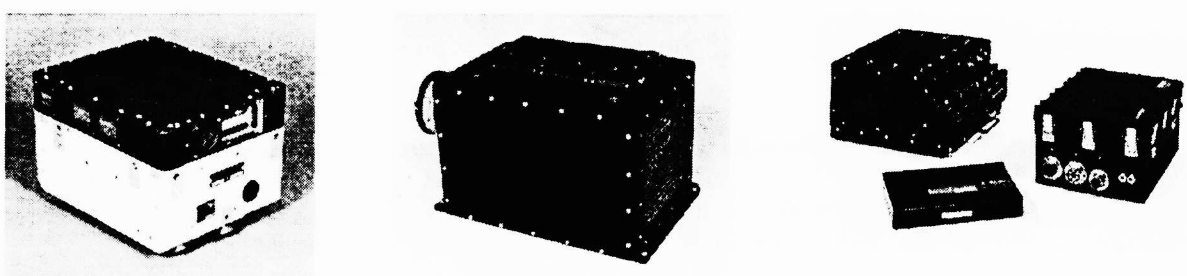


Figure 7. Ultra High Resolution Imaging Unit, Processing Electronics Unit and Digital Tape Recorder.

Electronic Image Motion Compensation

Image motion compensation or a very short exposure time is needed to produce an effective airborne reconnaissance camera. The Ultra High Resolution EO Framing Camera uses continuously graded on-chip motion compensation in conjunction with a focal plane shutter to allow operation from bright sunlight to dawn/dusk with exposure times typically between 1/3000 sec to 1/100 sec.

Image Motions

Image motions seen by a framing reconnaissance camera differ depending upon the camera look angle. As a reconnaissance aircraft passes over or near the area of interest, the segment of the ground being imaged by a camera appears to move. The manner in which the ground appears to move, and the extent of how much it moves, depends upon the flight parameters (altitude, velocity, etc.) and upon the orientation of the target area with respect to the camera (e.g., vertical, side oblique or forward oblique).

The presence of these motions introduces smear in the image during the exposure time. If the motions remain uncompensated, a greater or lesser degradation (depending on V/H) in image quality (resolution) results. In order to minimize such smearing of the image, various techniques for Image motion compensation (IMC) have been developed.

In the era of film-based cameras, these techniques have included moving the camera lens with respect to the film, moving the film with respect to the lens, and dynamically pointing the entire camera as a function of the changing relative position of the target. Today, using a ordinary frame transfer CCD detector array those fully mechanical compensation methods can be replaced by electronic methods with the same end result - an effectively motion free image, or one in which the residual motion is reduced to an acceptable level.

Figure 8 illustrates the types of image motions encountered when the camera is looking directly downward (vertical), looking toward one side (side oblique), or looking forward at a selected angle of depression from the horizon (forward oblique). In this figure, the rectangular focal plane array is shown as projected onto the ground. The relative magnitude and direction of the image motion within the frame is indicated by the length and direction of the motion-indicating arrows.

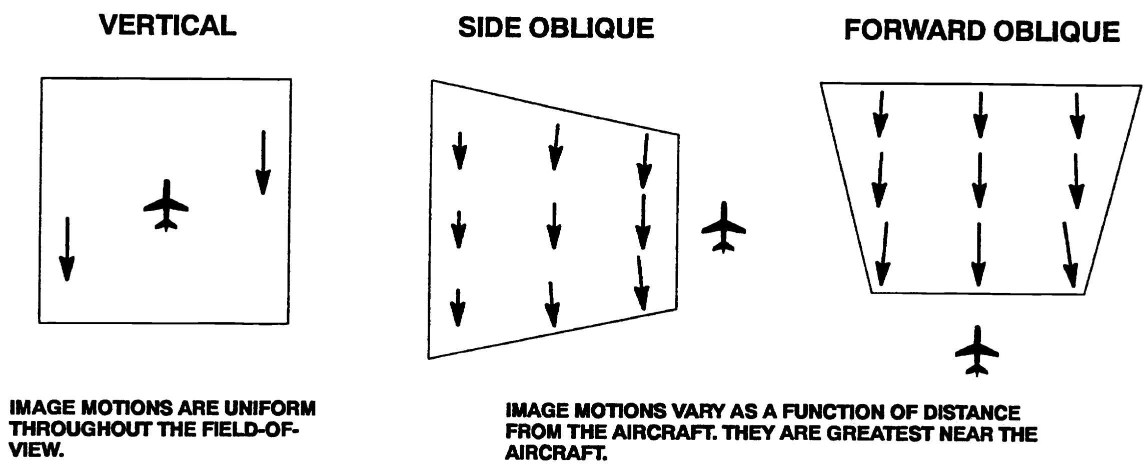


Figure 8. Image motions due to forward motion of aircraft vary with camera orientation

In the vertical example, all of the motion is of a singular direction and magnitude. That is, all the parts of the image move together, parallel to the line of flight. This motion is uniform in magnitude throughout the frame.

In the side oblique case, the motion remains parallel to the line of flight, but is not of the same magnitude throughout the frame. Objects nearest to the flight path appear to move fastest, while those further away from the line of flight appear to move more slowly, proportional to their distance away.

In the forward oblique, the image motion is composed of two vectors. The first is parallel to the line of flight as in the previous examples. Here again, the magnitude of this motion vector varies with range from the aircraft, and is larger the nearer a given point in the image is to the aircraft. Toward the edges of the frame, a second motion (of much lower absolute magnitude) occurs. As points approach the aircraft, they appear to "fly off" to the side of the format. Points to the left of the flight path "fly off" toward the left, and points to the right of the flight path "fly off" to the right. The magnitude of this vector increases the closer a given point is to the aircraft.

<u>**Image Motion Compensation**</u>

As previously indicated, the use of Charge Coupled Devices in place of film allows for a new method of "electronic" image motion compensation. In this method, the electronic signal being formed in the detector array by the image can be shifted to move along with the motion of the image falling on the array by activating the normal readout sequence during the exposure (TDI.)

As shown earlier, in either side oblique or forward oblique imaging applications, forward image motions are not the same at all positions in the field of view. In order to solve the problem of non-uniform image motion as a function of position of the object being photographed, it is necessary to alter the charge motion rate for each column (or group of columns). A simple way of accomplishing this is to keep the readout charge motion rate uniform throughout the entire chip and to continuously vary the uniform rate as a function of that portion of the imager which is being exposed by the open slit in a focal plane shutter at any given instant.

If a focal plane shutter is used, only a portion of the array is exposed at any one time through the moving slit of the shutter. Thus, if one matches the charge motion rate with the position of the slit as it traverses the chip, the optimum charge motion rate can be utilized for the exposed portion of the array. Since only one area of the array is exposed during the time associated with a given charge transfer rate, a nominally ideal image motion compensation can be obtained on-chip. This is referred to as continuously graded IMC. **Figure 9** illustrates the graded IMC concept as it would be used in the forward oblique imaging mode. The concept applies equally well in side oblique or vertical orientations. In side oblique applications the shutter is reoriented with respect to the array so that the vertical shift direction aligns with the slit length.

In any application the rate of change of charge motion is smooth and continuous with no segmenting or discontinuities. Thus, by taking advantage of the "metering" of imagery onto the array by the slit and the typical array readout process, image motion compensation is achieved.

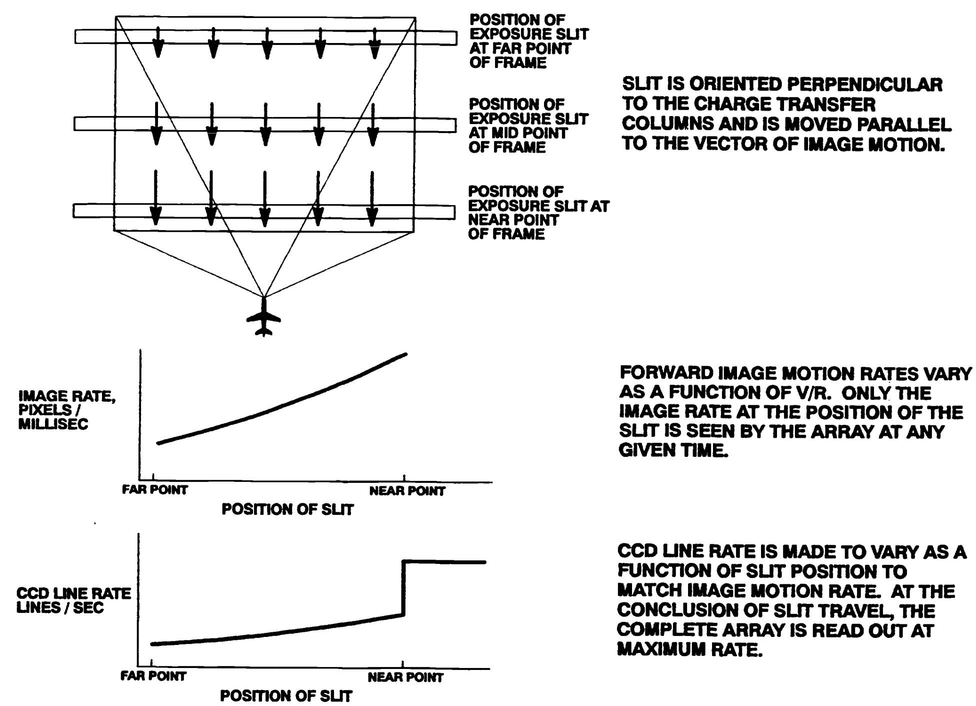


Figure 9. Operation of Graded IMC in the Forward Oblique mode. Ideal matching of the image motion and charge motion is achieved by simply varying the vertical readout clock rate during the exposure interval.

3. SUMMARY

The evolution of CCD technology has now made possible electronic cameras that rival the resolution and field of view of film cameras but offer wide dynamic range, real time image collection/dissemination and electronic processing for image enhancement, aided target detection and other automated processes. At 200 Mega pixels per second the Ultra High Resolution Camera should keep users busy for a while. However, this is surely not the end. The Ultra High Resolution Imager has enough pixels to support modifications to add RGB or other multispectral stripe filters. This can convert the imager into a land resource surveyor producing stereo pairs of multispectral data for exploitation by municipalities etc. More resolution, larger arrays, and even higher readout rates are possible. This will stress all of the networks shuttling data as well as data compression, data links, displays and exploitation algorithms.

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